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This report describes the work conducted over the past two decades on rail integrity research sponsored by the Federal Railroad Administration (FRA) and carried out by the Volpe National Transportation Systems Center. The research has involved both experimental and analytical studies on the subject of rail integrity. Brief descriptions of these various studies are given in this report for four different subtopics: analysis of rail defects, analysis of stresses in rail, strategies for rail inspection and testing, and other areas related to rail integrity research. These other areas of rail integrity research include advances in nondestructive inspection techniques, feasibility of advanced materials for rail, rail lubrication, and rail grinding and wear. The descriptions generally emphasize the development of analytical tools based on engineering principles that can provide rational strategies for dealing with rail aging due to service usage.

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PREFACE

The research described in this report was conducted in support of the Office of Research and Development of the Federal Railroad Administration (FRA). The FRA program manager for rail integrity research is Mr. Donald Plotkin.

This report describes rail integrity research conducted and managed by the Volpe National Transportation Systems Center (Volpe Center) over a two-decade period in support of the FRA's Track Safety Research Program. Particular emphasis is given to the development of analytical tools based on engineering mechanics principles.

The Rail Integrity Research Program has benefited from contributions by many railroad industry organizations, independent research laboratories, and universities. The Association of American Railroads has made major contributions through its management of rail integrity experiments conducted at the Transportation Technology Center.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

Inches	0			1		2			3		4			5	
Centimeters	0	1	2		3	4	5	6	7	8	9	10	11	12	13

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286 Updated 6/17/98

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

Table **Page**

LIST OF ABBREVIATIONS

AAR	Association of American Railroads
AREMA	American Railway Engineering and Maintenance-of-Way Association
BJR	bolted-joint rail
CUT	Cracow Institute of Technology
CWR	continuous welded rail
DARTS	Double Axis system for Residual stress, Texture, and Single crystal analysis
DF	detail fracture
DFG	detail fracture growth
DMS	decreasing maximum stress
EMAT	electromagnetic acoustic transducer
FAST	Facility for Accelerated Service Testing
FRA	Federal Railroad Administration
HA	head area
IEM	International Electric Machines, Inc.
MIT	Massachusetts Institute of Technology
MGT	million gross tons
MRS	mechanical roller straightening
NDI	nondestructive inspection
NIST	National Institute of Standards and Technology
RDF	reverse detail fracture
RDTF	rail defect test facility
RFD	rail flaw detection
RHT	rail heat treatment
RSO	real sequence order
SBIR	Small Business Innovation Research
SRS	Service Residual Model
TOSTM	Transverse/Oblique Slice Thermal Moiré
TTC	Transportation Technology Center
UHC	ultrahigh carbons
W/R	wheel/rail

EXECUTIVE SUMMARY

This report describes the progress of rail integrity research sponsored by the Federal Railroad Administration over the past two decades. In this context, rail integrity refers to control of the risk of rail failures which are generally caused by defects in the rail metal. Such defects form and grow in railroad rails from the repeated action of wheel loads exerted on the rail by passing trains. The growth rate of rail defects is relatively slow at first, but increases as the defect becomes larger. If the growth is allowed to continue unchecked, the defect will eventually reach a "critical" size at which the next wheel load will cause the defect to extend rapidly, fracturing the rail into two or more pieces. The period of time from when the defect becomes visible to crack-detection equipment to when the critical size is reached is referred to as the safe crack growth life. The safe crack-growth life is usually expressed in terms of tonnage (or million gross tons).

One of the objectives of rail integrity research is to provide guidelines for rail test frequencies based on the safe crack-growth life concept. This report describes the engineering tools that have been or are being developed for such purposes. Since rail integrity deals with management of defects, these engineering tools apply fracture mechanics principles. These engineering tools are validated with data obtained from tests conducted in the laboratory and in revenue service. One of these engineering models estimates the growth rate of a rail defect known as the detail fracture. Detail fractures account for about 75 percent of the rail defect population in continuous welded rail track in North America. The results from the engineering model for detail fracture growth indicate that residual stress, temperature differential, and track curvature have the strongest influence on the growth rate of such defects. Moreover, two of these three factors are the least controllable of all the factors considered in the growth rate studies. Consequently, recent work in rail integrity research has focused on understanding the development of residual stresses in railroad rail. Engineering models are now under development to estimate rail residual stresses from heat treatment and roller straightening during the manufacturing process and from cold working during in-service loading. Moreover, these engineering tools are being developed to provide information that may be used to derive scientific and rational strategies for managing the effects of service usage on rail integrity.

1. BACKGROUND

Rail integrity deals with the prevention and control of rail failures. Moreover, rail integrity affects the safety and economics of the railroad industry. Based on a study of accident data collected during the period from 1991 to 1997, the problems related to loss of rail integrity accounted for 30 percent of the harm resulting from train accidents.[1]

Rail failures usually occur because defects form and grow as the rail is subjected to repeated wheel loads. The presence of such defects weaken the strength of the rail to carry load. Consequently, research in rail integrity generally involves the application of fracture mechanics which is a discipline of solid mechanics dealing with structures containing defects in the form of detectable or visible sharp cracks.

The Office of Research and Development of the Federal Railroad Administration (FRA) has sponsored rail integrity research for several decades. Since the 1970's, the Volpe National Transportation Systems Center (Volpe Center) has been providing technical support to the FRA by managing and performing research for the FRA's Track Safety Research Program which includes a project on rail integrity.

The general objectives of rail integrity research are to improve railroad safety, via reduction of rail failures and the associated risks of train derailment; and railroad economics, via development of production or maintenance practices that increase rail service life. The general approach is to apply the principles of metal fatigue and solid mechanics to derive rational strategies for managing the effects of service usage on rail integrity. Nondestructive inspection (NDI) is a topic within the scope of rail integrity research.

Railroads have always inspected track visually to detect rail failures, and have been using crack-detection devices in rail test vehicles since the 1930's. Meanwhile, trends in the railroad industry have been to increase traffic density and axle loads. Therefore, current rail integrity research recognizes and addresses the need to review and update inspection strategies in light of the most recently developed applied fracture mechanics technology and railroad industry trends.

In general, the approach in conducting rail integrity research is similar to that of the damage tolerance design philosophy originally adopted by the U.S. Air Force, and now embraced by the commercial aircraft industry. The philosophy assumes that cracks will exist - caused either by initial manufacturing processes or by fatigue - and that fracture mechanics analyses and tests can be applied to check whether cracks can be detected by periodic inspection before they grow large enough to cause structural failure. In the context of railroad rails, damage tolerance is the capability of the rail to resist failure and continue to operate safely with damage (i.e., rail defects). This implies that a rail containing a crack or a defect is weaker than a normal rail, and that the rail strength decreases as the defect grows. As the growth continues, the applied stresses will eventually exceed the rail strength and cause a failure. The defect is said to have reached its

[1] "Harm" was defined in the study as a relative measure of loss resulting from a train accident. In this context, "harm" was calculated from a formula consisting of three factors: the number of fatalities, the number of injuries, and property damage.

critical size at the point of rail failure. Engineering fracture mechanics are used to determine the growth rate of rail defects and their critical size. Such information can then be used to establish guidelines for determining the appropriate frequency of rail inspections to mitigate the risk of rail failure from undetected defects.

Figure 1-1 shows a schematic of the different elements involved in applying the concepts of damage tolerance to rail integrity research. Generally speaking, damage tolerance, as applied to rail integrity, consists of three major parts: stress analysis, defect growth analysis, and inspection of rail defects. The principles of metal fatigue and solid mechanics are applied to analyze defect growth and rail stresses. The rate of crack growth depends on the defect type and the applied stresses, and usually increases as the defect grows. From an engineering mechanics point of view, stress analysis and defect growth depend on material, loading, and geometry. Results from the rail integrity research program indicate that in order to properly characterize the mechanical behavior of rail steel, effects from manufacturing processes such as heat treatment and roller straightening should be taken into account in the stress analysis. Specifically, these manufacturing processes contribute to the development of residual stresses (i.e., stresses that remain in an externally unloaded rail) which have a strong influence on defect growth rate. Quantifying the effects of residual stresses has been a considerable challenge because the residual stress distribution within the rail is known to change with service life. Loading is affected by train make-up because the rail bending moments depend not only on the weight of the car but on the spacing of the axles, trucks, and couplers. The factors that influence geometry are rail profile and type of defect. The rail profile affects the section properties (e.g., area moments of inertia, centroid, center of twist, etc.) that are necessary to calculate bending stresses. The rail profile can be altered by wear from in-service usage or by grinding from a deliberate maintenance practice. Clearly, different types of defects have different rates of growth.

Control of rail integrity is maintained by rail testing using specialized equipment. The process of rail testing is highly reliable but not perfect. Therefore, scheduling of rail testing must account for the possibility of undetected defects that remain in rail. In principle, the frequency of rail testing should depend on the defect growth rate. In practice, scheduling of rail tests also depends on other factors such as resource allocation. A part of rail integrity research is to explore alternative strategies to current practice that would optimize the frequency of rail testing and resource allocation while maintaining an equivalent level of safety.

Ultrasonics and magnetic induction are the primary methods of choice for rail testing. Research is ongoing to examine the application of other technologies such as electromagnetic acoustic transducers to complement the existing methods.

Another aspect of the rail integrity research program has been to disseminate technical information developed under the research through technical reports, papers published in professional journals, and conference proceedings. A listing of the various documents produced during the course of the research is provided in the References.

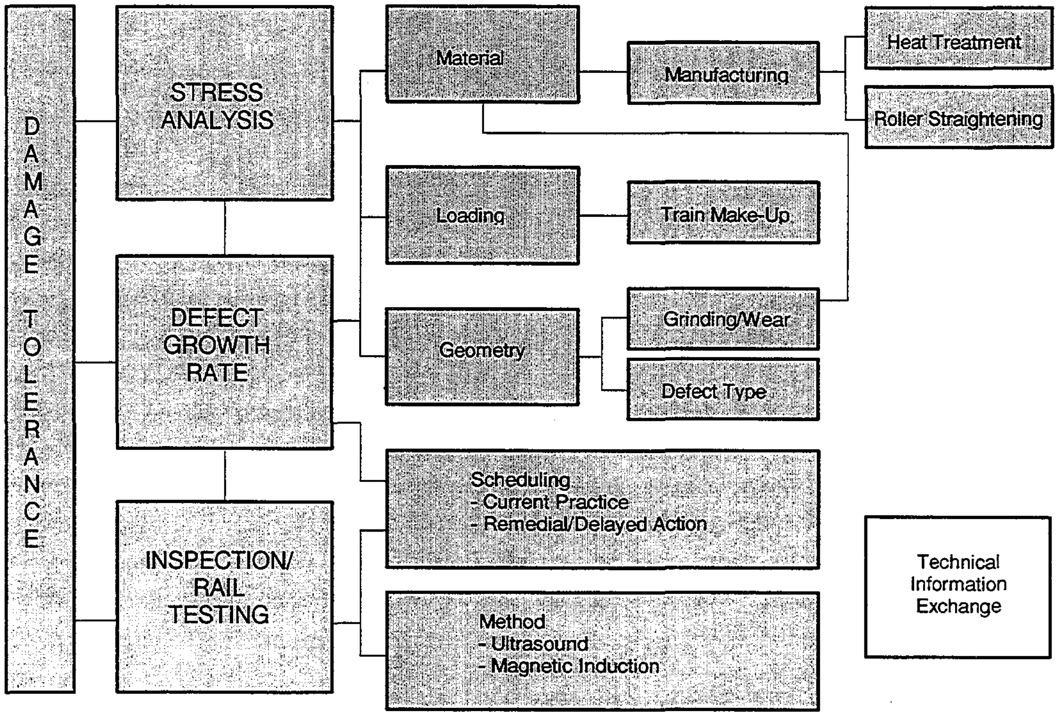

Figure 1-1. Elements of Damage Tolerance Approach to Rail Integrity Research

In carrying out the damage tolerance approach as outlined in Figure 1-1, several engineering analysis tools have been and are being developed and validated to examine various aspects of rail integrity. Figure 1-2 shows a schematic of five engineering models that provide input information to each succeeding model. For example, residual stresses are initially created in rail during heat treatment, but are affected later in the manufacturing process when the rail is roller straightened and subsequently during in-service usage. Thus, three models are under development to examine the evolution of residual stresses as the rail is heat treated, roller straightened, and used in service. Knowledge of the residual stress state in the rail is then used in fracture mechanics-based models to examine the growth of transverse defects in the rail head. Specifically, a fracture mechanics-based model was developed for a particular transverse rail head defect known as the detail fracture. This model is referred to in Figure 1-2 as the Detail Fracture Growth Model, and is described in Section 2-2. Once the defect growth rate is known, then rail testing strategies can be developed and evaluated using a simulation model.

This report describes the experimental and analytical efforts performed during the course of the FRA/Volpe Center rail integrity research program. Following this introductory section, previous and current research activities are described by reviewing the state-of-the-art in the analysis of rail defects, analysis of stresses in rails, and strategies for inspection or rail testing. Finally, recommendations for future work are given.

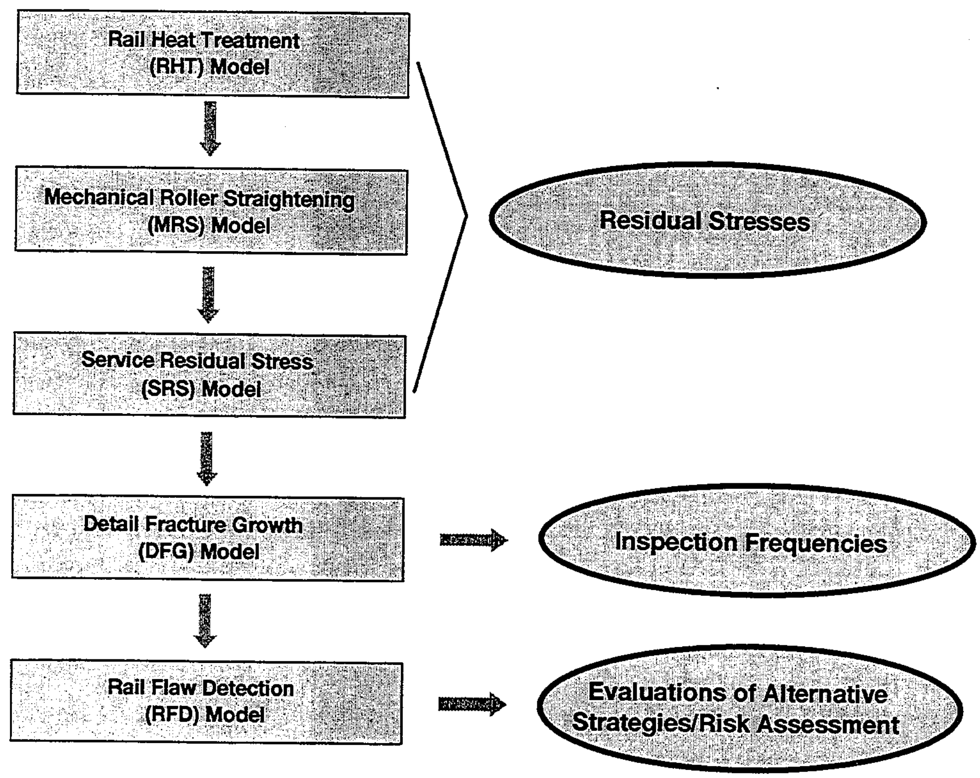

Figure 1-2. Rail Integrity Analysis Tools

2. ANALYSIS OF RAIL DEFECTS

In principle, rational strategies can be developed to deal with the problems associated with rail defects if their growth rate is known. Track design, maintenance, train operations, and other factors can affect the mechanical behavior of rail defects. Analytical modeling provides an approach to examine the effect that various factors have on the mechanical behavior of rail defects. Data obtained from controlled experiments to monitor rail defects can then be used to validate the analytical models.

The mechanical behavior of rail defects typically comprises two stages: formation and growth. Analytical studies on defect formation have been conducted as part of the rail integrity research program to determine the number of defects that can be expected to enter the population, the intervals of service life over which they appear, and the distribution of their locations in track. Analyses on defect growth have been conducted to determine the intervals of service life over which defects can be expected to evolve to larger sizes if not detected. Service life for both formation and growth is usually expressed in terms of train traffic or tonnage in million gross tons (MGT). Moreover, the industry generally reports rail service ages in terms of accumulated MGT and traffic densities in annual MGT (i.e., MGT per year).

Figure 2-1 shows how the different types of defects contribute to the harm resulting from railroad accidents. The bar chart indicates that detail fractures, transverse and compound fissures, and other rail and joint bar defects account for over 40 percent of the harm resulting from accidents caused by loss of rail integrity.

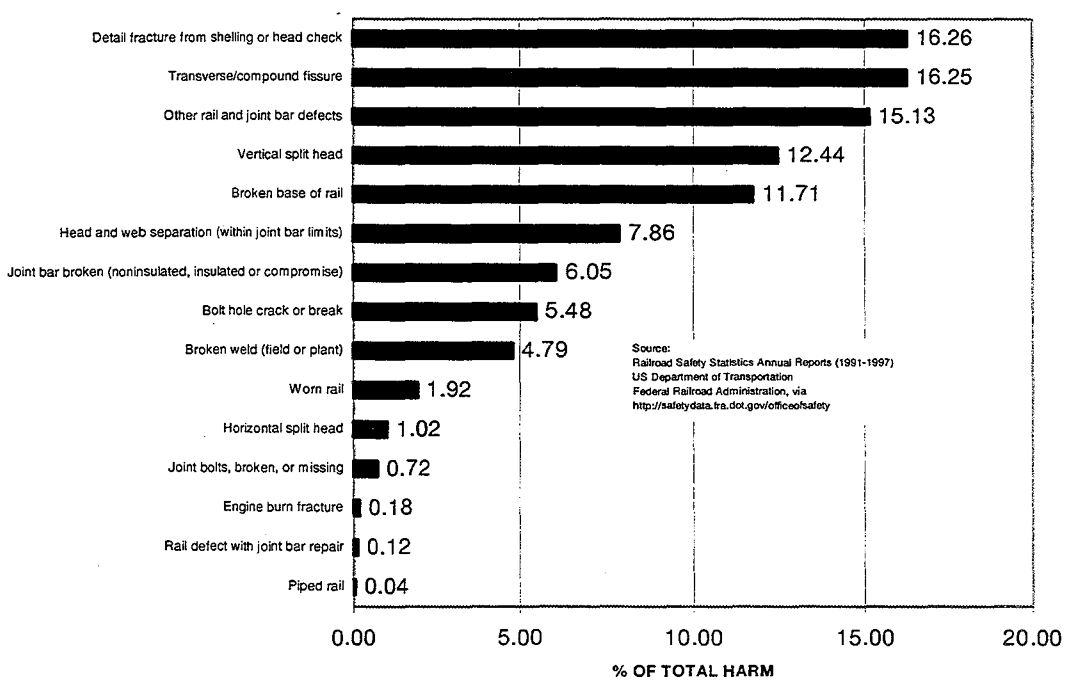

Figure 2-1. Distribution of Harm for Railroad Accidents Due to Rail Integrity Causes (Based on Accident Data Collected from 1991 to 1997)

The FRA/Volpe Center rail integrity research has primarily focused investigations on two types of rail defects: transverse internal defects and bolt-hole cracks. Some studies have been performed to examine other rail defects such as vertical split heads and web cracks. But particular focus has been given to an internal transverse rail defect known as the detail fracture because it accounts for about 75 percent of the rail defect population in continuous welded rail (CWR) track in North America. Bolt-hole cracks account for about half of the defect population in bolted-joint rail (BJR) track. A trend in the railroad industry, however, has been to replace BJR with CWR. Consequently, detail fractures are expected to be the predominant rail defect encountered in railroad rail.

According to the *Rail Defect Manual* published by Sperry Rail Services, a detail fracture is a progressive fracture starting from a longitudinal separation close to the running surface of the rail head, then turning downward to form a transverse separation substantially at right angles to the running surface. Figure 2-2 shows a detail fracture originating from an internal horizontal crack called a shell. Shells are typically located between 6 to 10 millimeters (mm) beneath the running surface of the rail. Because its orientation is horizontal or parallel to the running surface, shells are not considered to pose a direct threat to rail structural integrity. On the other hand, because detail fractures (DFs) are oriented in the transverse direction, which is perpendicular to the running surface, DFs do pose a direct threat to rail integrity.

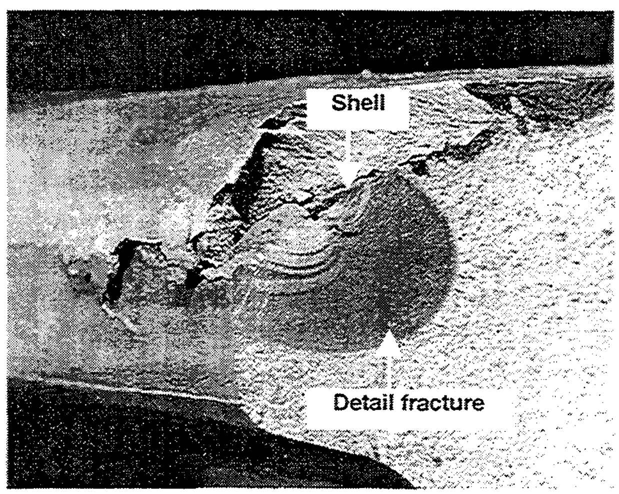

Figure 2-2. Broken Rail Showing Shell Origin of Detail Fracture (Courtesy of Transportation Technology Center, Inc.)

Although shells are not classified as rail defects, a small proportion of shells form downward branching cracks that become detail fractures. Initial modeling efforts, however, assumed that fatigue life corresponded to the formation of detail fractures. At a later stage in the model development, it was recognized that the fatigue life prediction ought to be based on shell formation. The models to examine shell formation are discussed as follows.

2.1 ANALYSIS OF SHELL FORMATION

The formation of shells in rails had become prevalent in North America by the mid-1940's, but it was not until the early 1970's that analytical methods were applied to predict their formation. The engineering models developed to examine shell formation approximate the rail as a beam on a continuous elastic foundation and assume that wheel/rail forces create Hertzian contact stresses[2] in the rail head. Moreover, the models were developed to predict the life to shell formation and the location where a shell may be expected to occur within the rail head.

The initial model was based on a uniaxial stress analysis (Perlman, et al., 1982). In the model development, rail replacement was recognized as being governed by a competition between fatigue and rail wear. Wear was modeled as loss of rail head height per 100 MGT.[3] The model predicted that detail fractures originate at the running surface. This prediction was based on assuming that the defect origin coincides with the location where the longitudinal stress is a maximum. The largest contributor to the longitudinal stress in the model was the contact stress which was calculated from the Hertz theory for circular cylinders at right angles. Such Hertzian contact stresses, however, are well above the yield strength of rail steel. Results from sensitivity studies conducted with this model showed that the fatigue life of 70 ASCE rail exceeded the lives of 115 RE and 132 RE sections. These spurious results were artifacts from applying the general Hertz contact theory. The sensitivity studies also showed that the predicted fatigue life was extremely sensitive to wear rate and relatively insensitive to residual stress which were contrary to expectations. At this stage of the model development, however, it became apparent that the fatigue life prediction ought to be based on shell formation rather than the formation of detail fractures which actually branch from established shells. Since shells tend to form in a nearly horizontal plane, a model for shell formation should be based on either vertical or triaxial[4] stresses rather than longitudinal stresses.

Subsequently, an alternative model was developed based on a triaxial stress analysis (Jeong, et al., 1987) in which the contact stresses were calculated from assuming line contact (i.e., parallel circular cylinders in contact). The line contact solution appears to give more realistic estimates of contact stress in the rail head than the general Hertz theory. Moreover, the triaxial stress-based model predicted that the location of the shell origin was about 2 to 4 mm higher than the observed location of shell formation. The location of the predicted shell origin coincides with the location of the maximum effective stress,[5] but the reason for the discrepancy between the predicted and observed location of the shell origin is unknown at this time.

The engineering models predicted that the first percentile[6] of shells appear between 70 and 200 MGT for a range of parameters that represent typical revenue service conditions. These values for the first percentile fatigue life are roughly consistent with field observations of shell forma-

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2 Contact stresses are caused by the pressure of a wheel on a rail over a limited area of contact. Hertzian contact stresses refers to contact of two elastic bodies, which is a simplifying assumption.

3 A typical value assumed in the model was 0.03 inch per 100 MGT.

4 A triaxial state refers to the simultaneous presence of stress acting in different directions.

5 Effective stress is a quantity used to relate a triaxial state of stress to a material property such as yield strength.

6 First percentile life means the time at which 1 percent of a large sample of specimens can be expected to have formed a crack.

tion. In this respect, the engineering models developed for shell formation provide qualitative results that are encouraging.

However, additional refinement is needed to calibrate the results to field data because the predicted effect of some factors on shell formation were contrary to field observations. For example, results from sensitivity studies using the triaxial stress-based model showed that the rail bending effect is weak. Specifically, fatigue life was found to be insensitive to rail size and foundation modulus. The triaxial stress-based model also predicted that fatigue life was insensitive to wear rate.

Alternatively, the life-to-shell formation N (in MGT) can be estimated by correlating rail defect data with a Weibull distribution model (Weibull, 1951):

$$F(N) = 1 - e^{-(N/\beta)^{\alpha}} \tag{1}$$

where α is a shape factor[7] and β is a scale parameter. In correlating the Weibull model with data obtained from six locations on two railroads (Besuner, et al., 1978), values of α were found to range between 2.9 and 5.5, and the range of values for β were from 1,200 MGT to 3,000 MGT.

From the Weibull model, the first percentile life-for-shell formation in rail subjected to mixed freight traffic is estimated to be between 430 and 490 MGT (Orringer, 1990), which represents the time required to grow rail defects to a detectable size as well as to form them. As such, the first percentile life for shell formation as given by the Weibull model should be expected to exhibit longer life than the engineering mechanics models. The difference in the fatigue lives given by the Weibull and the engineering mechanics models could be interpreted as the time for a shell to turn down and branch to become a detail fracture.

While some preliminary work has been conducted by the Association of American Railroads (AAR - Farris, et al., 1992), the development of a mechanics-based model to examine turning or branching of a shell into a detail fracture has not been completed, and appears to be a formidable task.

Shell formation life may be considered to represent an economic limit which can be useful in developing guidelines for scheduling rail replacement. A more comprehensive review of the research conducted on shells in rail can be found in a separate document (Steele, 1988).

2.2 ANALYSIS OF TRANSVERSE DEFECTS IN THE RAIL HEAD

Fracture mechanics principles can be applied to examine the fatigue and fracture strength of rails containing defects of detectable or visible size. In the fracture mechanics approach, different types of rail defects can be analyzed by varying mathematical expressions for the crack driving force or stress intensity factor. Once the stress intensity factor for a given crack or defect is

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7 The Weibull probability density function with a shape factor of α=3.4 resembles a normal (i.e., Gaussian) distribution.

known, the state of stress in the vicinity of the crack tip is completely defined, and growth of the crack can be predicted.

In the FRA/Volpe Center rail integrity research program, studies of defect growth have concentrated on an internal rail head defect called the DF because it is the most common type of fatigue defect encountered in CWR. DFs become detectable by ultrasonic testing equipment when they cover about 5 percent of the rail head cross-sectional area (% HA),[8] and can be detected with virtual certainty at about 30 percent of the head area.

Various models to examine the growth of detail fractures are described in this section. The first is an engineering model that approximates the rail as a beam on a continuous elastic foundation and uses basic stress intensity factor formulas. The second applies the finite element method and advanced fracture mechanics principles. Another advanced fracture mechanics concept is used to develop models to examine the effect of load sequence on defect growth rate. This section also describes a model to analyze another type of rail head defect called the reverse detail fracture.

In general, the models described in this section calculate the safe crack-growth life of a rail defect under specified conditions (e.g., rail section, residual stress, train makeup, track curvature, etc.). In the present context, safe crack-growth life refers to the time it takes a defect to grow from minimum detectable size to critical size. Here, "critical size" means the size of the defect at which rail failure may be expected to occur under the next train. Moreover, the safe-crack growth life defines the window of opportunity to find the defect.

2.2.1 Engineering Model for Detail Fracture Growth

The engineering model for detail fracture growth is based on a linear elastic fracture mechanics solution for an elliptical crack embedded in the rail head (Orringer, et al., 1988). The detail fracture was modeled with basic stress intensity factor formulas that were modified to account for the effects of finite boundaries and stress gradients.

The model was initially calibrated by correlating results with data obtained from six rails tested at the Facility for Accelerated Service Testing (FAST) at the Transportation Technology Center (TTC) in Pueblo, Colorado. The FAST experiment was run from mid-June through mid-December 1982. The engineering model was later validated with data from 12 other detail fractures in a second FAST experiment on 5° to 6° curved track[9] (Clayton and Tang, 1992). The model validation also included correlations with data from compact-tension specimens tested in the laboratory which simulated the growth of detail fractures. The experimental procedure for this simulation was developed by the Massachusetts Institute of Technology (MIT) (Journet and Pelloux, 1987); and was applied later by the Instron, Corp. (Jablonski, et al., 1990). The crack growth data produced from the experimental simulations was within reasonable agreement (i.e., within 10 to 20 percent) with the field test data collected at FAST.

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8 The sizes of transverse defects, such as detail fractures, are generally given in terms of percent rail head cross-sectional area where the percentage is based on the area for brand new or unworn rail.

9 This validation required a minor change in the way that rail residual stress is modeled for detail fractures smaller than 10% HA.

The engineering model was based on material properties for rail steel determined through experiments performed by MIT (Scutti, et al., 1984; Journet and Pelloux, 1988). Such experiments were conducted using compact tension specimens that were machined from the center of actual rail heads. The fatigue crack growth rate data obtained from these experiments were correlated to the following crack growth rate equation:

$$\frac{da}{dN} = C\frac{\Delta K^p}{(1-R)^q} \tag{2}$$

where a is the characteristic size of the defect, N is the number of stress cycles, ΔK is the stress intensity factor range, and R is the stress ratio.[10] In the crack growth rate equation, C, p, and q are empirical constants. Table 2-1 lists the values of the empirical constants that provide a reasonable approximation to the crack growth rate data.

Table 2-1. Empirical Constants for Crack Growth Rate Equation

C		p	q
(SI units)	(English units)		
1.74×10^{-13} m-(MPa-m$^{1/2}$)$^{-4}$-cycle^{-1}	1.00×10^{-11} inch-(ksi-inch$^{1/2}$)$^{-4}$-cycle^{-1}	4	1.63

Other crack growth rate equations may be used to predict the growth of rail defects. In a study comparing two crack growth rate models (Tang et al., 1991), equation (2) was found to be more suitable to use in comparing predicted lives with results from variable amplitude or spectrum tests over thousands of cycles.

Sensitivity studies were performed with the engineering model for detail fractures (Orringer, et al., 1988) to examine the relative effect of track design, maintenance, operational, and other factors on safe crack-growth life and critical size (i.e., size of the detail fracture at which rail failure may be expected to occur). The results of the sensitivity studies are summarized in Table 2-2. Two of the three factors that have the strongest influence on both the safe crack-growth life and critical size, namely, temperature differential and residual stress may be the least controllable of all the factors considered. For example, temperature differential depends totally on the vagaries of the weather. Control of residual stresses can be exercised through manufacturing and/or rail grinding, but the procedures to accomplish such control are not well understood at present.

[10] The stress ratio is the minimum stress divided by the maximum stress in a given cycle. In fatigue crack growth experiments conducted in the laboratory, the tests are conducted at constant amplitude so that the stress ratio does not vary. In actual service loading conditions, however, the stress ratio varies from cycle to cycle.

Table 2-2. Sensitivity of Factors on Predictions for Detail Fractures

Effect	*Factor*	
	Safe Crack-Growth Life	*Critical Size*
Strong	Temperature differential Residual stress Track curvature	Temperature differential Residual stress Dynamic load factor
Moderate	Rail section Track foundation stiffness Location of wheel/rail contact Average axle load	Rail section Track foundation stiffness Track curvature Average axle load
Weak	Dynamic load factor Location of defect center	Location of wheel/rail contact Location of defect center

2.2.2 Advanced Fracture Mechanics Model for Detail Fracture

Modeling of detail fractures was also performed using a three-dimensional finite element stress analysis (Sih and Tzou, 1984). In this model, the detail fracture was initially assumed to be a 5 percent HA circular flaw embedded in the rail head. The shape of the propagating defect was then determined by calculating the energy release rate at discrete points around the periphery of the flaw and applying the strain energy density criterion.[11] Although the model uses a three-dimensional stress analysis, some simplifying assumptions were made. For example, a static wheel load of 19 kips was assumed to create a single stress cycle. In addition residual and thermal stresses were neglected. Figure 2-3 shows the predicted growth patterns, which appear to resemble the shapes of actual detail fractures. Moreover, the calculated crack growth lives were of the same order as those observed in service. The calculations needed to execute this model can become tedious because the three-dimensional finite element grid must be updated after each increment of growth. For this reason, limited studies were performed with the three-dimensional finite element model for detail fractures. The results from this model, however, demonstrate an application of fracture mechanics concepts and provides additional confidence in the fracture mechanics approach to analyze rail defects.

[11] The strain energy density criterion is a fracture mechanics theory that can be used to predict the direction and amount of crack growth (Sih, 1973).

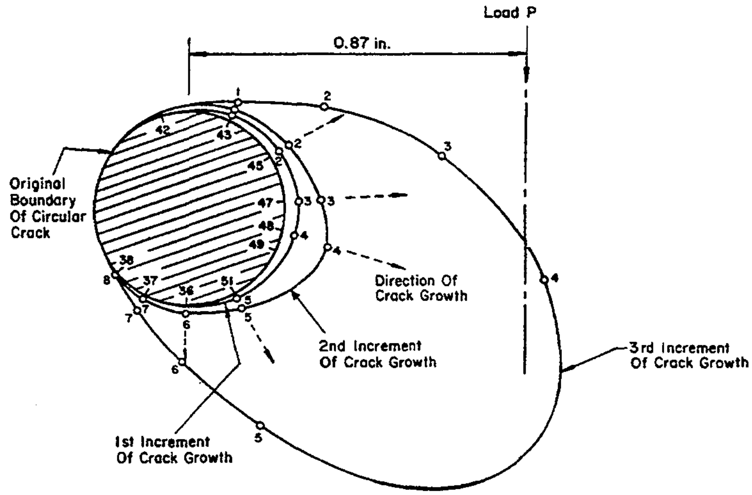

Figure 2-3. Incremental Growth of Detail Fracture Predicted from Advanced Fracture Model (from Sih and Tzou, 1984)

2.2.3 Effect of Load Sequence

Experiments in which laboratory specimens are subjected to variable amplitude or spectrum loading have shown that crack growth rate depends not only on the current stress cycle but on the stresses of prior cycles as well. That is, the sequence of load application appears to have an effect on crack growth rate. However, the models described previously for analyzing detail fractures neglected the effect of load sequence.

Historically, the differences in the crack growth behavior of aircraft aluminum due to load sequence have been explained by crack closure[12] (Elber, 1970; Elber, 1971). Analytical (Jeong and Sih, 1990; Sih and Jeong, 1992) and experimental (Jablonski and Pelloux, 1992) studies were performed to examine load sequence effects and the role of crack closure on the fatigue crack growth behavior of rail steel. Closure loads were measured during laboratory experiments using compact tension specimens subjected to two different load sequences or spectra. The first spectrum was a reconstruction of the stress cycles created from a train consisting of typical freight cars used at FAST, and is referred to as the real sequence order (RSO) spectrum. The reconstruction was performed by calculating the vertical bending component of the rail head stress using beam theory approximations. The combined effect of thermal and residual stress was represented by a fixed mean stress of 15 ksi. The second spectrum was created by rearranging the order of the RSO spectrum according to decreasing maximum stress. For this reason, the second spectrum is referred to as decreasing maximum stress (DMS). The trends of the results from the laboratory experiments and the crack closure calculations were consistent in that the DMS lifetime is longer than the RSO lifetime. But the ratios of DMS to RSO lifetime was 2:1 in

[12] Crack closure refers to a phenomenon when the opposing surfaces of a crack are in contact with each other. In the context of fatigue crack growth behavior, it is assumed that a crack does not propagate when the crack surfaces are in contact (i.e., during crack closure).

ments, and 3:2 in growth calculations with crack closure. Therefore, the cause of load sequence effects in rail steel remains an open question.

2.2.4 Engineering Model for Reverse Detail Fracture

The engineering model for detail fractures was modified to examine the growth of a another transverse defect that occurs in the rail head, provisionally called a "reverse detail fracture" (RDF - Jeong, et al., 1998a). Figure 2-4 is a photograph of this type of internal defect which indicates that the rail is heavily worn.[13] It is speculated that RDF defects occur in poorly lubricated, curved, worn rail on stiff track carrying traffic with high axle loads. The origin of the RDF defect is at the lower gage corner of the rail head rather than below the running surface near the upper gage corner where detail fractures usually initiate. This type of defect had not been examined in previous research. Comparing results between the detail fracture and reverse detail fracture, the growth rates are initially comparable, but the safe crack-growth life for RDF defects is about 20 percent shorter than that for detail fractures under the same conditions. The percentage of the rail defect population that comprise RDF defects is unknown. RDF defects occasionally occur near thermite or butt welds, and generally occur at a shear lip in the rail head which is created from plastic flow. The correlation between the RDF-defect occurrence and its location relative to welds may suggest an influence of the heat-affected zone from welding. The correlation between RDF defect occurrence and shear lip formation suggests that a local stress concentration at the shear lip may promote defect formation. These aspects of RDF defect behavior have not been investigated.

Figure 2-4. RDF Defect in Lower Gage Corner of the Rail Head (Courtesy of Sperry Rail Service)

[13] The rail shown in Figure 6 is 136 RE, which has an unworn rail head width that is slightly less than 3 inches.

2.3 ANALYSIS OF BOLT-HOLE CRACKS

Bolt-hole cracks account for about half the rail defects in jointed track. They originate in the rail joints at the corner between the rail web and the surface of the bolt hole. Bolt-hole cracks generally emanate from the hole closest to the rail end at approximately ±45° from the vertical until the crack reaches the rail head or base (Figure 2-5). Formation of bolt-hole cracks is believed to result from fretting fatigue when the shank of the bolt bears against the surface of the hole in a loose joint.

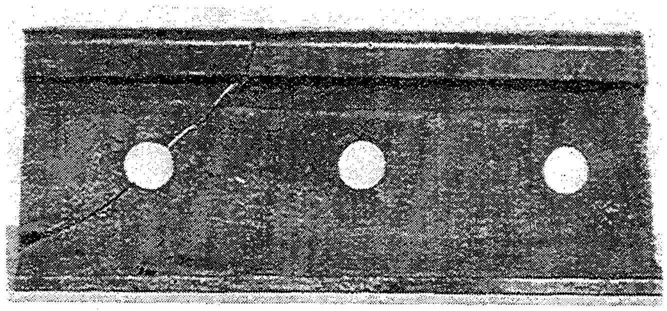

Figure 2-5. Bolt-Hole Crack in Rail

Experimental and analytical studies of bolt-hole cracks have been performed by Arthur D. Little, Inc. (Mayville and Hilton, 1984; Mayville, et al., 1990). The results from the laboratory experiments revealed that the stress intensity factor was nearly independent of crack length between detectable size[14] and critical size (Mayville, et al., 1990) which greatly simplifies the crack growth calculation. Moreover, calculations based on a simplified stress spectrum and the experimentally determined stress intensity factor showed that about 10 MGT are required to grow a bolt-hole crack from detectable to critical size.

A more detailed analytical model of bolt-hole cracks (Sih and Tzou, 1985) was performed using a three-dimensional finite element stress analysis in conjunction with the strain energy density criterion. The strain energy density criterion was applied to determine the branching and trajectories of the cracks emanating from the bolt hole. The results of the finite element analysis suggest that bolt-hole cracking causes rail fracture by propagating and penetrating into the rail head before reaching the base. Moreover, the predicted crack trajectories resembled those found from actual rail-end fragmentations, providing further confidence in the application of fracture mechanics concepts to analyze rail defects.

In modeling the growth rate of bolt-hole cracks, the mechanics of the bolted joint should be incorporated. For example, a bolted joint is assumed to carry a moment that is less than the moment carried in a continuous rail. The ratio of the moment carried by the bolted joint to the moment carried by a continuous rail is called the joint bar efficiency factor. A finite element beam model was developed to relate the joint bar efficiency factor with the gap distance between the

[14] A bolt-hole crack becomes detectable when it penetrates the thickness of the rail web, or about 0.6 inches.

rail and the joint bars (Mayville and Stringfellow, 1993). The gap distance was considered as a measure of the joint looseness. The results of the finite element beam model indicated that the joint bar efficiency factor decreases from 0.85 to 0.60 as the gap between the rail and joint bars increases from zero to 0.030 inches for a 132 RE rail. Dynamic loads created by the impact of the wheel upon a loose joint were also calculated. The results of these finite element calculations suggest that bolt-hole cracks are at a greater risk of fracture when the joint is loose, which is consistent with general field experience.

2.4 OTHER RAIL DEFECTS

Defects known as vertical split heads occur in the center or the gage side of the rail head. These defects appear to originate from inclusion stringers. A general relation between crack length and probability of detection for this type of defect is not known. Fractographic studies of vertical split head defects have been performed (Mayville, 1985). The results of these studies suggest that the length of the stringer colony determines the length of the vertical split head. Finite element analyses (both two- and three-dimensional) have been conducted to determine mixed-mode stress intensity factors for a kinked vertical split head crack (Mayville and Stringfellow, 1993). Crack growth calculations based on these analyses indicate that more than 200 MGT are required before a vertical split head will break out to the surface.

Defects in the rail web also have been examined. The effect of residual stresses as a driving force to propagate web cracks was examined by Wineman and McClintock (1987). The effect of fatigue, from repeating wheel loads during in-service traffic, on web cracks has also been examined using both an elementary engineering model and a three-dimensional finite element analysis (Jeong and Orringer, 1989). The safe crack-growth life of web cracks was strongly sensitive to the level of residual stress. However, assuming a tensile residual stress level of 20 ksi, corresponding to the largest assumed magnitude of tensile residual stress in the analysis, about 1200 MGT are required for a web crack to grow from 0.1 inch to 0.2 inch. No experimental data are available to verify this result. However, the calculated growth rate represents extremely slow growth when compared to other rail defects.

3. ANALYSIS OF STRESSES IN RAIL

Stresses in railroad rails may be considered as the superposition of several components. These components include contact, bending, thermal, and residual stresses. Contact stresses play a significant role in the analysis of defect formation, but are negligible in the analysis of defect growth because detail fractures are located deep enough below the running surface to where the contact stresses have completely decayed.[15] Rail bending stresses are created from the continuous repetition of wheel loads on the rail. Thermal stresses are created from thermal expansion, and are calculated only for CWR. Residual stresses occur from manufacturing processes and cold working during in-service usage. Moreover, residual stresses have been found to play a significant role in rail defect behavior. Each of these components except contact stresses is discussed in this section.

3.1 BENDING STRESSES

The calculation of bending stresses in the engineering models for transverse defects in the rail head is based on the classical theory of beams on elastic foundation. In particular, the theory developed by Timoshenko and Langer (1932) has been applied to analyze stresses in rail. A simplified version of the Timoshenko and Langer analysis was developed (Orringer, et al., 1986), and has subsequently been used in the analysis of detail fractures and RDF defects. Similarly, the semi-infinite beam on elastic foundation theory (Hetenyi, 1983) was used to analyze bolt-hole cracking.

As mentioned previously, three-dimensional finite element models have been developed to examine detail fractures (Sih and Tzou, 1984) and bolt-hole cracks (Sih and Tzou, 1985). Finite element analyses have also been performed by Battelle Columbus Laboratories to determine stresses in rail (Johns, et al., 1981).

3.2 THERMAL STRESSES

Thermal stresses can be calculated for fully restrained CWR in tangent track from

$$\sigma_{TH} = E\alpha(T_N - T) \tag{3}$$

where E is the modulus of elasticity, α is the linear coefficient of thermal expansion, T_N is the stress-free or neutral temperature, and T is the rail service temperature. When considering crack-growth behavior, thermal stresses are detrimental when tensile. In practice, the calculation of thermal stresses from equation (3) can become slightly complicated because studies have shown that the rail neutral temperature does not remain constant and may vary cyclically with a decreasing trend (Kish, et al., 1987). The effect of varying thermal tension can be taken into account in the defect-growth models if the variation of the temperature difference or thermal stress is known a priori.

[15] The contact stresses in the rail head have completely decayed within 1 inch of the running surface.

3.3 RESIDUAL STRESSES

Residual stresses are those that remain in an externally unloaded rail. The nature of residual stresses in the rail head is such that an interior region comprising one-third to one-half of the rail head cross-section is in a state of triaxial tension, which promotes the formation and growth of defects in that particular region. The fatigue and fracture models developed under the rail integrity research program demonstrate the significance of residual stresses. For example, the models to predict the growth of transverse defects in rail (Orringer, et al., 1988; Jeong, et al., 1998a) were strongly sensitive to the level of residual stress. In addition, the triaxial stress-based model for predicting shell formation (Jeong, et al., 1987) was moderately sensitive to residual stress. Further discussion on the effects of rail residual stress on rail performance can be found in a separate document (Orringer, 1993).

The sources of residual stresses are: (a) heat treatment during manufacturing, (b) roller straightening, and (c) in-service loading.[16] Initially, research focused on understanding the development of residual stresses from the plastic deformations caused by the repetition of wheel loads during revenue-service traffic. Moreover, the quantification of residual stresses by either experimental or analytical means has been found to be a relatively difficult task. Another source of residual stresses in rails could be from welding. To date, however, the development of rail residual stresses from welding has not been investigated in the rail integrity research program.[17]

3.3.1 Prediction Methods

Repeated wheel passages over rails creates cyclic plastic flow which in turn induces residual stresses that affect the formation and growth of shells, detail fractures, and vertical split heads. The residual stress field is believed to stabilize to a quasi-steady state or so-called shakedown state at an early point in the life of a rail as cyclic work hardening increases the material's resistance to permanent deformation. During controlled experiments where a rail was loaded repeatedly along the same contact patch, between 2×10^5 and 1×10^6 wheel passes were required to fully develop the residual stress field (Świderski and Wójtowicz, 1992). More wheel passes are required in actual service to reach the shakedown state because the center of contact wanders across the running surface as a rail encounters wheels with different profiles. It has been estimated that between 10 to 100 MGT of traffic are required to fully develop residual stresses in rail (Orringer, 1993).[18]

A computational methodology has been developed to predict the residual stress distribution at the shakedown limit. The methodology is based on elastic-plastic finite element models in conjunction with nonlinear optimization algorithms (Orkisz and Harris, 1988; Orkisz et al., 1990). The finite element method is used to determine the local variations in stress that satisfy equilibrium conditions. The optimization method is used to determine the energy states corresponding to possible shakedown levels. Yield strength, load magnitude and sequence, presence of initial

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[16] Research is ongoing to examine the effect of rail grinding on residual stresses (see Section 5.4).

[17] The development of residual stresses from welding of tank car steels is currently being examined in support of the FRA's Rail Equipment Safety Research Program.

[18] Assuming an average axle load of 33 tons, 10 to 100 MGT of traffic is equivalent to about 3×10^5 to 3×10^6 wheel passes.

stresses, and lateral wheel wandering were found to affect the predicted residual stress levels and distribution (Orkisz and Holowinski, 1993). Other computational methods such as the hybrid finite element method (Holowinski and Orkisz, 1992; Perlman and Gordon, 1992) and the boundary element method (Cecot and Orkisz, 1992) have also been applied in this methodology.

The influence of initial stresses on the final residual stress state indicates that manufacturing processes such as roller straightening should be considered in the prediction of residual stresses. Roller straightening produces residual stresses in rail through cold working. Studies have been performed to predict residual stresses from roller straightening using finite element models and a simple analytical model (Wineman, 1991). A three-dimensional finite element model to examine roller straightening of rail is now under development.

Efforts have recently begun to understand the residual stresses produced from heat treatment during rail production. Three-dimensional thermoplastic finite element models are under development for this purpose (Fata, et al., 1998; Jones, et al., 1998). Residual stresses develop in rail from quenching because the rail cools non-uniformly due to the complex cross-section. Predictions from these models are consistent with experimental observations of hardened layer depth in modern heat-treated rail. Figure 3-1 shows the axial residual stress distribution along the vertical centerline of the rail, as predicted by the model for in-line head-hardening heat treatment. Moreover, the figure shows that the maximum level of tensile axial residual stress occurs in the interior of the rail head which has been confirmed by experimental measurements.

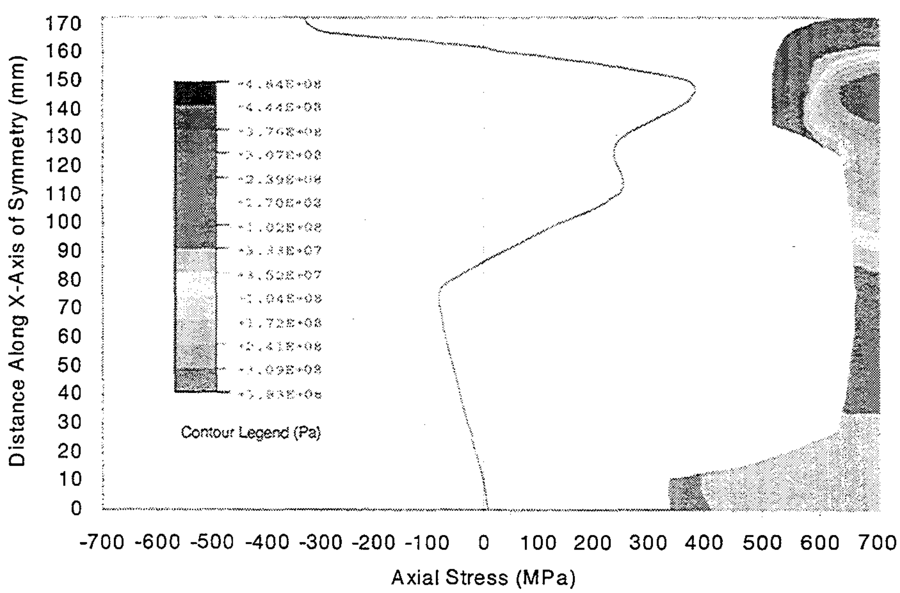

Figure 3-1. Axial Residual Stresses Predicted from Thermoplastic Finite Element Analysis (from Fata, et al., 1997)

3.3.2 Methods to Relieve and Determine Residual Stresses

To date, the methods to determine residual stresses in rails are destructive. Stresses are relieved by either sectioning (i.e., cutting) or high-temperature annealing (i.e., heat treatment). The deformations or strains associated with the stress relief are measured. Residual stresses are later inferred from the measured quantities through a data-reduction method based on solid mechanics principles.

The method of sectioning or cutting of rail into small slices and cubes was developed by Battelle Columbus Laboratories (Groom, 1983). Before the rail was sectioned, the rail was instrumented with gages so that strains could be measured as stresses were relieved from cutting. In 1983, nine rail samples were examined with this technique at a cost of $20,000 per sample. One of the disadvantages of the method is that stresses can be introduced when the rail is cut. Also, the resolution of the residual stress field depends on the size of the cubes since only the average stress in a cube can be inferred.

An alternative method to relieve residual stresses was developed at the State University of New York (SUNY) at Stony Brook (Wang and Chiang, 1993) where stress relief is achieved through high-temperature annealing. In this method, interferometry was applied to measure the deformations associated with stress relief. In theory, no additional stresses are introduced by heating as long as the temperature does not exceed the re-crystallization temperature. The thermal annealing method to determine rail residual stresses was most recently applied to rail samples obtained from the rail grinding experiment at FAST (Wang and Chiang, 1997; Wang et al., 1999). This approach has been referred to as the Transverse/Oblique Slice Thermal Moiré (TOSTM) method. During the conduct of these measurements, however, gratings from two rail samples were destroyed during the thermal annealing process.

In-situ residual-stress measurements can be made using X-ray diffraction, but the present method is limited to determining stresses on the surface of a given sample. The application of neutron diffraction[19] to measure rail residual stresses was explored through an inter-agency agreement between the Volpe Center and the National Institute of Standards and Technology (NIST). Rail slices similar to those that were used in the high-temperature annealing method were used with the neutron diffraction technique (Gnäupel-Herold, et al., 1999). The neutron diffraction measurements were carried out using a specially developed system called DARTS, which is an acronym for Double Axis system for Residual stress, Texture, and Single crystal analysis. The residual stress measurements from the neutron diffraction method appeared reasonable. The magnitudes and locations of the maximum tensile stresses were consistent with previous experimental results. It remains to be seen, however, whether DARTS can be applied to measure in-situ longitudinal residual stresses in the head of an actual rail section (i.e., nondestructively).

[19] The neutron diffraction measurement technique is similar to X-ray diffraction, but neutron radiation penetrates about a factor of 1000 deeper into steel than X-rays do. Thus, it is possible to perform stress measurements at locations beneath the surface of the specimens.

3.3.3 Data-Reduction Methods to Determine Residual Stresses

Residual stresses were initially inferred from rail sectioning by assuming elastic unloading and applying the tangent modulus theory of elasticity (Groom, 1983). But rail cutting may induce reverse plastic flow in regions with high residual stresses. Therefore, an advanced data reduction method to determine residual stresses from the interferometry measurements is being developed by the Cracow University of Technology (CUT). Although this data reduction method will account for plastic deformation, it is also assumed that purely elastic unloading occurs during stress relief which neglects the Bauschinger effect.[20]

The procedures developed by SUNY at Stony Brook and CUT will be applied specifically to analyze the data obtained from rail samples that were used in the TOSTM method and the experiments conducted on the FAST loop at TTC. In particular, the effects of different rail grinding patterns on the development of rail residual stresses will be examined. In these studies, residual stresses are considered as a measure of rail performance since they have a significant effect on the formation and growth of rail defects. Moreover, these studies will investigate how rail grinding may be used to control rail integrity by altering the magnitude and distribution of residual stresses in the rail head through grinding.

[20] The Bauschinger effect is usually observed in metals when a specimen is plastically deformed in one direction of loading and then a reverse load is applied in the opposite direction. The Bauschinger effect occurs when the specimen plastically deforms in the reverse loading direction at a stress level less than the corresponding yield strength.

4. STRATEGIES FOR INSPECTION/RAIL TESTING

A major goal of rail integrity research is to provide technical information that may be useful to help in formulating industry guidelines for inspecting rail in the United States. Current practices for rail testing must comply with 49 CFR 213. Moreover, alternative procedures should provide an equivalent level of safety to current practices. In this section, two examples are described where results of rail integrity research were integrated to achieve this objective.

4.1 ADAPTIVE SCHEDULING FOR RAIL INSPECTION

In 1990, the results of rail integrity research were integrated in the development of a self-adaptive guideline for scheduling of rail tests to detect detail fractures (Orringer, 1990). Here, "self-adaptive" means that the frequency of rail inspection is varied according to the total rate of defect occurrence per test, the rate of defects found by means other than scheduled tests, and tonnage of traffic carried between tests. The guideline included a provision for fine tuning inspection frequency to account for changes in performance of rail inspection equipment. The guideline was developed on the basis of rail defect population statistics from four U.S. railroads in the late 1970's (Orringer and Bush, 1983). In a field trial where the guideline was applied on one line, the railroad saved $70,000 per year from decreasing inspection frequency while maintaining the established level of safe performance. Moreover, a benefit from optimizing inspection frequency is that resources can be allocated according to need.

4.2 RISK/BENEFIT ANALYSIS FOR DELAYED REMEDIAL ACTION ON RAIL REPLACEMENT

Results of rail integrity research were integrated during the development of a model that simulates detector-car utilization on a hypothetical railroad line (Tang, et al., 1995). The simulation model was based on Monte Carlo methods. Moreover, the model was developed to evaluate a test waiver requested by a major North American railroad. The waiver is based on the concept of "non-critical" defects. In this context, the term "non-critical" refers to defects less than a certain size. Under current practice, immediate remedial action (such as a speed reduction, reinforcement with angle bars, rail replacement, etc.) must be taken when a defect is discovered in a rail. With this restriction, a repair crew or chase gang closely follows the detector car which can limit the number of inspected track miles per day. The test waiver allows "non-critical" defects to remain in-service for a grace period that would potentially increase detector car utilization.

A damage tolerance approach was adopted in evaluating the concept of non-critical defects for rail replacement. Moreover, the engineering model for detail fractures was used to determine the specific conditions for the waiver (Jeong, et al., 1997). Based upon the results from this damage tolerance approach, the waiver was granted to the railroad with the following conditions: a 4-day delay period for detail fractures 20% HA or less in winter (defined as November 15 to March 15),[21] and a 5-day grace period for defects 25% HA or less in summer.

[21] The waiver also specifies a special cold weather provision, where no delayed action is allowed if the service temperature for a particular day is anticipated to be below 0°F.

The simulation model and the engineering model for detail fractures were applied to evaluate the concept of delayed remedial action for "non-critical" defects (Orringer, et al., 1999). The model assesses "risk" as the potential number of missed detections from underestimating defect size during rail testing; "benefit" is defined by the number of increased miles of detector-car utilization, which provides more opportunity to detect defects ahead of rail failure. The results from the model suggest that delayed remedial action for "non-critical" defects may be a worthwhile concept from a railroad safety viewpoint. It should be emphasized that in order for this concept to succeed, rail testing equipment must not only reliably detect the presence of a rail defect but also must accurately measure its size once a defect has been found.

5. OTHER AREAS OF RAIL INTEGRITY RESEARCH

5.1 ADVANCES IN NONDESTRUCTIVE INSPECTION TECHNIQUES

Rail testing has become the primary method for controlling rail defects. A summary of the methods used for rail testing is given in the *Rail Defect Manual* compiled by Sperry Rail Service (also see Orringer and Ceccon, 1980). Ultrasonic testing equipment was introduced in the 1960's and 1970's, and is the most common technique used today. Ultrasonic equipment, however, may not detect internal defects if there are shells large enough or if the running surface is corrugated or contains heavy head checking. Also, lubrication on top of the rail may inhibit detection of internal defects. Recent improvements in magnetic induction technology[22] appear to overcome these shortcomings in ultrasonic detection. These advances are currently being developed for practical applications. The coupling of ultrasound and magnetic induction as complementary technologies for rail testing should improve the overall reliability in detecting defects. In another research effort, the FRA awarded an SBIR (Small Business Innovation Research) project to International Electronic Machines, Corp. (IEM) in Albany, New York, to develop advanced NDI technology based on electromagnetic acoustic transducers (EMATs). Phase I of this SBIR program was completed in July 1996. The results of the Phase I study demonstrated the feasibility of applying EMAT to detect internal defects in rail with head checking (Mian and Arthur, 1996). A Phase II was initiated in 1998, with the objective of developing a prototype EMAT system for field operations.

In 1997, a facility was constructed at the TTC to evaluate the performance of various types of rail flaw detection equipment. This facility is called the Rail Defect Test Facility (RDTF), and was built under the joint sponsorship of the AAR and the FRA. In 1998, the facility was used to evaluate six ultrasonic inspection systems. At that time, the facility contained over 70 flaws which were supplied by AAR member railroads. The results of these evaluations were published in an AAR research report (Garcia and Reiff, 1999). In 1999, the facility was extended in overall length from about 1,890 feet to over 5,400 feet. With this extended length, the facility contained over 80 flaws from revenue service and 50 artificial flaws. Benchmark evaluations were performed on the extended RDTF. These evaluations showed that performance of the detection equipment was comparable to the guidelines recommended by the American Railway Engineering and Maintenance-of-Way Association (AREMA). Modifications to the RDTF are planned for 2001 in which the track facility will be divided into two sections. One section will contain 30 to 40 rail defects over 4,000 feet of track. This section will be used to evaluate systems where detector cars may operate at speeds approaching 15 mph or more. A second section will contain between 75 to 100 rail defects over 1,440 feet of track, and will be used primarily for development of new and improved technologies for rail flaw detection.

[22] Magnetic induction was actually the first method successfully applied to detect rail defects, and was the primary method for about 40 years until the widespread use of ultrasonic equipment.

5.2 FEASIBILITY OF ADVANCED MATERIALS FOR RAIL

Improvements in rail steel quality in terms of fatigue, fracture, and wear resistance have been achieved conventionally by: (1) increasing carbon content, (2) adding alloying elements, (3) heat treatment, (4) improving metallurgical cleanliness by reducing inclusions,[23] or (5) work hardening. Rail quality improvements through these methods have strived to maintain a pearlitic microstructure. For future rail applications, however, alternative methods to improve rail quality may be required to offset the railroad industry's trend in carrying heavier axle loads over their rails. One possible method to achieve improvements in fatigue, fracture, and wear resistance may be the production of rail steel with a carbide-free or bainitic microstructure. Such a microstructure could be attained by controlling the in-line quenching during rail production and/or altering the rail steel chemical composition by adding alloys such as chromium, vanadium, and molybdenum. A technical study is being conducted to evaluate the feasibility of producing bainitic rail steel. The preliminary outlook is that bainitic steel appears to be suitable for application to frogs.

Other potential methods to improve rail strength may be investigated such as maraging[24] steels and ultrahigh carbon (UHC) steels. Finite element analyses modeling heat treatment of rail may be useful to evaluate the options to improve rail strength. For example, a thermoplastic finite element model has been developed to examine the problem of designing quenching schedules for the production of bainitic rail (Jones, et al., 1998). The results of this model suggest that further study is needed to determine whether bainitic rail can be straightened, by means of conventional cold-rolling processes, without leaving excessive residual stresses in the rail when it enters service.

5.3 RAIL LUBRICATION

Some railroads lubricate rails to reduce wheel and rail wear and to save fuel. Experiments at the TTC have demonstrated such benefits. But these experiments have also shown that the occurrence of fatigue-crack formation increases significantly in lubricated rail (Steele and Reiff, 1982). Wear is the principal life-limiting factor for rail, but as rail wear life is extended, many more rails stay in service long enough for fatigue cracks to form and propagate. The research studies on rail lubrication have been conducted by the AAR at the TTC, and have been empirical in nature.

5.4 RAIL GRINDING AND WEAR

Some railroads grind the rail head to maintain specific profile shapes. The intent of rail grinding is primarily to control rolling contact conditions and rail wear. Some recent field observations and theoretical studies have indicated that particular grinding patterns may either adversely or beneficially affect residual stresses and fatigue cracking behavior in rail (Perlman, et al., 1993).

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[23] Metallurgical cleanliness can be quantified in terms of chemical composition by the oxide and sulfide content.

[24] Maraging steels have low-carbon content, but contain a relatively large percentage of nickel and other hardening elements. With heat treatment, maraging steels can attain ultrahigh strength.

Recent experiments also have been conducted at the TTC on the High Tonnage Loop[25] at FAST (Clayton and Hannafious, 1997). Table 4-1 summarizes the different grinding patterns and frequencies that were varied in these experiments. Five pairs of transverse and oblique rail slices were cut from each of these conditions. The rails were 136 RE in size, and 300 HB in Brinell hardness.[26] The neutron diffraction technique was applied to these rail slices to measure residual stresses (Gnäupel-Herold, et al., 1999). Moreover, the results from these measurements appear to indicate that grinding has beneficial effects on rail fatigue life.

Table 4-1. Conditions Tested in Rail Grinding Experiments at FAST

No.	*Description*
1	Control specimen, no grinding
2	FAST worn profile, ground every 25 MGT
3	Two-point contact, ground every 12.5 MGT
4	Two-point contact, ground every 25 MGT
5	Brand new rail, not installed in track

Although the FRA Track Safety Standards do not address rail wear, technical information has been developed under the rail integrity research program to estimate wear limits based on rail strength (Jeong, et al., 1998b). These analyses assumed that wear occurs as uniform loss of material from either the top of rail or the gage-side face.[27] Rail section properties that are required for the beam-theory stress analysis were estimated for these two rail wear patterns. Rail wear limits were estimated on the basis of strength criteria that consider failure as either permanent bending or fracture. The fracture-based wear limits were found to be more restrictive (i.e., more conservative) than those based on permanent bending. Moreover, the fracture-based wear limits appeared to be comparable to those used by a major U.S. railroad.

This methodology to develop wear limits was subsequently used to examine the effect of wear on the safe crack-growth life of rail head defects. The analyses showed that wear had a moderate effect on the growth of detail fractures, and a strong to moderate effect on the growth of reverse detail fractures.

[25] The average axle load on the High Tonnage Loop at FAST is 39 tons.

[26] Hardness testing is usually performed by impressing an indenter of fixed and known geometry into a specimen. Depending on the type of test, the hardness is expressed by a number related to the depth of indentation. When a Brinell Hardness Test is performed, the hardness number is followed by the symbol HB.

[27] For curved track in general, gage-side wear usually occurs on the high rail, and loss of head height occurs on the low rail.

6. SUMMARY

Several engineering analysis tools have been and are being developed and validated in the FRA/Volpe Center rail integrity research program.

Fracture mechanics principles have been applied to compute the safe crack-growth life of rail defects under specified conditions (rail section, residual stress, train makeup, track curvature, etc.) from minimum detectable size to a size at which rail failure is expected to occur under the next train. The safe crack-growth life is computed in terms of MGT. Particular attention has been given to the detail fracture because it is the most common rail defect encountered in continuous welded rail track in North America.

Advanced finite element techniques are being applied to compute the residual stresses expected in a rail due to repeated application of service loads. The service loading is specified as an envelope of peak loads, and the model has the capability to compute residual stresses for peak loads having an unpredictable sequence of lateral locations (i.e., simulation of realistic wheel/rail contact effects). The outputs of these finite element models are the location, magnitude, and extent of residual longitudinal tension in the rail head. Moreover, these characteristics directly affect the safe crack-growth life of detail fractures as well as other types of transverse defects in the rail head.

Conventional finite element technology is being applied to compute the temperature versus time history and residual stresses developed by quenching heat treatments such as those employed in the manufacturing of head-hardened rail. Rail metallurgical microstructure can be inferred from the temperature versus time history output, and the residual stress output can be used as a specification of initial residual stresses for use as input to calculate the residual stresses developed during service loading.

Monte Carlo methods have been applied to simulate defect detection performance on a hypothetical railroad line assumed to contain growing detail fractures subjected to periodic inspection by a rail flaw detection vehicle. The inputs to the Monte Carlo simulation model include seasonally adjusted defect growth rates, based on the fracture mechanics model for detail fracture growth, and a curve of detection probability versus defect size, based on empirical estimates from field experience. The outputs of the simulation model include annual detected defects per track mile inspected, service/detected defect ratio, and detector car utilization (average miles inspected per day) for various specified annual tonnages and inspection frequencies.

Models are under development to simulate the mechanical effects of the roller straightening processes used for finishing rail to meet camber tolerances. Such models will compute the residual stresses due to roller straightening. The magnitude of these stresses can be used as an indicator of sudden fracture risk, and the detailed stresses can be used as input information to the other models.

7. RECOMMENDATIONS FOR FUTURE RESEARCH

Rail integrity research is an ongoing effort, and will continue as annual tonnages and average axle loads increase on the nation's railroads. The following recommendations for further research are given, in no particular order of importance or priority.

1. The original data used to validate the detail fracture model were obtained from rails produced in the 1950's and 1960's. The yield strength of standard carbon steel rail of that era was about 70 ksi, and the Brinell hardness was about 250 HB. Rail quality has improved over the last two decades so that yield strength is equal to about 90 ksi, and the Brinell hardness equal to about 300 HB. It appears reasonable to assume the fracture toughness, fatigue life, and crack propagation life of rail may have changed as well. Therefore, experiments similar to the original FAST tests should be performed using modern rail to determine defect growth behavior under service conditions. After the test on the FAST loop is completed, the rails should be broken open to map the contours of the fracture surface to estimate the growth rate from fatigue striation marks. Residual stresses in the rail head should be measured with the most modern and accurate methods to date. The ambient temperatures during the test should be recorded. If possible, the neutral temperature variation should also be monitored and recorded. In addition to field service data, laboratory tests using compact tension specimens may also be required to obtain fracture toughness (K_{IC}) and crack growth rate data for modern rail steel.

2. One way to evaluate the difference between "old" and more modern rail would be to execute the shakedown models to predict residual stress assuming different values of yield strength depending on rail vintage, as described in paragraph number 1. In other words, a comparison between a yield strength of 70 ksi versus 90 ksi could be examined to estimate the difference in residual stresses between older and modern rail which in turn affect predictions of safe crack-growth life in transverse defects.

3. A model to estimate the potential error in ultrasonic measurement of transverse defects (particularly, detail fractures) has been developed to estimate the probability that a defect will be incorrectly classified as one that is actually larger. Because the model was based on a limited sample size, additional data are needed for measured versus true defect sizes.

4. The computational methods predict residual stresses in uncracked rails or rails without defects. What is the effect of redistribution of residual stress as a crack grows through the residual stress field?

5. The location of wheel/rail (W/R) contact position "wanders" on the rail crown. Some preliminary analyses are being conducted to determine the possible range of W/R contact positions and load intensities that may occur under normal revenue-service conditions. This information is currently being generated as input data for the calculation of rail residual stresses from the computational models. Such information also can be applied to calculations for safe crack-growth life, if it is known what percentage of time the W/R contact position is located at a given location.

6. Once the computational models to determine rail residual stresses have been fully developed, they can be exercised to estimate the internal stress distribution within the rail head. These results coupled with the results from paragraph number 5 can then be applied to the defect-growth models. For example, residual stress results from the heat treatment and roller straightening models can provide input to calculate shell-formation life from the triaxial stress-based model. The foregoing residual stress results also can be used as input to determine the shakedown state, which in turn, can be used as input to estimate safe crack-growth lives of transverse defects. These defect-growth rates then can be used to update the guideline for scheduling of rail tests and the simulation model for detector-car utilization.

7. The neutron diffraction technique (DARTS) can be applied to an actual rail section to determine the feasibility of measuring residual stresses with this technology. Rather than using transverse and oblique rail slices, which were used in the previous work with neutron diffraction (Gnäupel-Herold, et al., 1999), a section of rail could be used. By using a piece of an actual rail section, the residual stresses in the longitudinal direction of the rail would be preserved. Moreover, if this measurement technique is successful, the reliability of the procedures to reconstruct rail residual stresses from the transverse/oblique slice method can be established.

8. Nondestructive inspection of rail defects is highly reliable but not perfect. For example, detection of internal defects under shells or heavy surface damage can be difficult. Research is needed to overcome these difficulties. In addition to reliable detection of internal rail defects, detection equipment must also accurately determine the size of the defect if alternative inspection strategies such as the delayed remedial action concept are to be successful.

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NOTE: References preceded by an asterisk (*) were prepared in support of the FRA/Volpe Center Rail Integrity Research Program.

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